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Measuring and Estimating the Bioconcentration Factor of Chemicals in Fish

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Measuring and Estimating the Bioconcentration Factor of Chemicals in Fish

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VEITH, G. D., D. L. DEFOE, AND B. V. BERGSTEDT. 1979. Measuring and estimating the bioconcentration factor of chemicals in fish. J. Fish. Res. Board Can. 36: 1040–1048.

A method of estimating the bioconcentration factor of organic chemicals in fathead minnows (*Pimephales promelas*) is described. Water at 25 C was intermittently dosed with the chemical at a nontoxic concentration in a flow-through aquarium. Thirty minnows are placed in the aquarium, and composite samples of five fish are removed for analysis after 2, 4, 8, 16, 24, and 32 d of exposure. The bioconcentration process is summarized by using the first-order uptake model, and the steady-state bioconcentration factor is calculated from the 32-d exposure. A structure-activity correlation between the bioconcentration factor (BCF) and the *n*-octanol/water partition coefficient (*P*) of individual chemicals is summarized by the equation $\log BCF = 0.85 \log P - 0.70$, which permits the estimation of the bioconcentration factor of chemicals to within 60%, before laboratory testing. The facilities and resources for testing need be used only for those chemicals that are likely to result in substantial bioconcentration in organisms. The bioconcentration factors derived from tests of mixtures of chemicals are shown to be the same as those derived from tests with the chemicals individually.

Key words: bioconcentration factor, bioaccumulation, structure-activity, bioassay

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Les auteurs décrivent une méthode d'estimation du facteur de bioconcentration de substances chimiques organiques chez des têtes-de-boule (*Pimephales promelas*). Ils ont analysé de façon intermittente l'eau à 25 C avec la substance chimique à une concentration non toxique dans un aquarium à flot continu. Trente têtes-de-boule ont été placées dans un aquarium et des échantillons de cinq poissons ont été prélevés pour fins d'analyse après 2, 4, 8, 16, 24 et 32 d d'exposition. On résume le processus de bioconcentration à l'aide d'un modèle d'absorption de premier ordre et calcule à partir de l'exposition de 32 d le facteur de bioconcentration au point d'équilibre. On exprime une corrélation structure-activité entre le facteur de bioconcentration (BCF) et le coefficient de partition *n*-octanol eau (*P*) de substances chimiques individuelles par l'équation $\log BCF = 0{,}85 \log P - 0{,}70$ permettant l'estimation du facteur de bioconcentration des substances chimiques en dedans de 60%, avant les essais en laboratoire. Il n'est pas nécessaire d'utiliser installations et ressources pour ces essais pour des substances chimiques autres que celles qui sont susceptibles de causer une importante bioconcentration dans les organismes. Les auteurs démontrent que les facteurs de bioconcentration dérivés d'essais avec mélanges de substances chimiques sont identiques à ceux obtenus avec substances chimiques individuelles.

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THE use of bioconcentration factors as an estimate of the residue-forming potential of organic chemicals has become increasingly important in testing protocols for ranking chemicals as possible hazards to the environment. These protocols require an understanding of the overall physical meaning of the term "bioconcentration factor," the precision with which the factor can be measured or estimated, and the costs involved with refining the adequacy of the bioconcentration factor if the protocols are to be successful.

The objectives of this study were to develop a laboratory method for estimating the bioconcentration potential of chemicals in fish and to determine whether the bioconcentration potential is related to the *n*-octanol/water partition coefficient of the chemical. The first objective is necessary to help standardize bioconcentration testing. The second objective is necessary for the development of less expensive screening techniques to eliminate the need from bioconcentration testing if chemicals are not likely to form significant residues in the biological systems.

Bioconcentration is the accumulation of a chemical residue in fish by transport of the chemicals through the gills or other membranes and excludes accumulation by the consumption and absorption of contaminated food. The bioconcentration factor (BCF) is a constant of proportionality between the concentra-

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tion of the chemical in the fish (C_F) and in the water (C_W) as follows:

$$C_F = C_W \times \text{BCF}.$$

This definition requires that the concentration of a chemical in fish be linearly related to the concentration in the water.

Various models are available to approximate bioconcentration in aquatic organisms. They are all based on the assumption that the uptake and depuration processes can be estimated by simple first-order kinetic expressions. Pentreath (1973), Branson et al. (1975), and Krzeminski et al. (1977) proposed that uptake was first order with respect to the water concentration and that depuration of the chemical from fish was first order with respect to the concentration in the fish. Therefore, the rate of change in the residue would be

$$\frac{dc}{dt} = K_1 C_W - K_2 C_F$$

where K_1 and K_2 are the uptake and depuration rate constants. When C_W is constant, the increase in residue in the fish is given by the equation

$$C_F = (K_1/K_2)\, C_W\, (1 - e^{-K_2 t}).$$

Similarly, Ernst (1977) used the kinetic approach to determine the bioconcentration factor for pesticides in mussels.

Measurements of BCF can be made by exposing organisms for a period sufficiently long that the steady-state residue is observed, or relying on the accuracy of a given kinetic model to measure appropriate rate constants and calculate the BCF assuming the chemical behaved according to the model. For large fish, at low temperatures, or with chemicals with a large BCF, the time required to reach steady state may be too great to be generally used in a routine testing program. In these instances, it is likely that the kinetic method proposed by Branson et al. (1975) may be the most economical approach. The uncertainty of this approach is that the BCF is estimated from the initial uptake rate constant which may change with time of exposure, and from the depuration rate constant which may not always be adequately expressed by a single rate constant. Moreover, the BCF calculated from this method does not always have a residue measurement at or near steady state.

The uptake process can be accelerated by using smaller fish at higher temperatures which decreases the time to reach steady state and permits a few measurements to be made near the steady-state conditions. Using the kinetic approach, these conditions would likely give greater confidence for chemicals with large BCF; however, it would be difficult to measure accurately the uptake rate constant for chemicals with low BCF. For chemicals of low BCF, simply measuring the BCF at steady state may be most reliable.

Neely et al. (1974) have shown for eight chemicals that the BCF can be estimated from the *n*-octanol/water partition coefficient by using the equation

$$\log \text{BCF} = 0.542 \log P + 0.124.$$

This equation resulted from the correlation of BCF for rainbow trout and estimates of log P. It is perhaps the most rapid method of estimating BCF for chemicals in trout, although such estimates are based on a very small number of measured values.

Materials and Methods

Exposure System

The bioconcentration factor of a chemical can be measured by using any system that provides (1) a constant, sublethal concentration of the chemical in test water; (2) an adequate environment for fish with respect to physiologically important characteristics such as temperature and dissolved oxygen; and (3) an adequate carrying capacity with respect to numbers of fish so that sufficient samples can be taken for measuring the uptake process. The exposure can be conducted in a typical bioassay diluter or in a single-tank exposure system that produces constant water concentrations. Although several different systems have been used in this study, only the system finally developed specifically for bioconcentration testing will be outlined.

A row of 1.0-L cells was constructed similar to that in the conventional Mount and Brungs diluter (Mount and Brungs 1967) complete with siphon tubes. When the cells filled with water completely, the overflow activated a 40-s timer as well as the siphons that transfer water from metering to mixing cells. The timer energized a chemical-metering pump (Fluid Metering Incorporated, Model RPG, 0-1.6 mL/min) for 40 s, which metered the test chemical from the reservoir into the mixing cell. The concentration in the water was controlled by adjusting the metering-pump flow rate.

The mixing cell was a 1500-mL beaker cemented inside the 30-L aquarium used for the exposure. A 6-mm hole was drilled 25 mm from the bottom of the beaker, which allowed the entire litre of water and the chemical dose to mix and drain into the test chamber for ~2 min. The water flow rate was controlled by the filling rate of the 1.0-L measuring cells, which was ~400 mL/min. Small variations in filling rate do not affect the concentration of the chemical because the metering pump is operated for a constant period during each delivery of 1.0 L of diluent water. The water from the overflow drain in each tank was passed through an activated carbon filter to remove the chemical from the wastewater and then through a stainless-steel heat exchanger before being discharged. The recovered heat was used to preheat the lake water going to the headbox.

The test water was Lake Superior water, which was heated to a mean temperature (±SD) of 25 ± 0.5°C and brought to dissolved gas saturation in the headbox that delivered water to the glass measuring cell. The mean (±SD) hardness and alkalinity of the water were 45.5 ± 0.97 mg/L (as $CaCO_3$) and 41.5 ± 1.2 mg/L (as $CaCO_3$), respectively, as determined from 208 measurements of each during this study. The arithmetic mean of the pH was 7.49 ± 0.15. Dissolved oxygen varied with the number of fish in the tanks and was maintained >5 mg/L by a flow rate >250 mL/min to each tank.

Test Organisms

The test organism used in the majority of tests was the fathead minnow (*Pimephales promelas*), although rainbow trout (*Salmo gairdneri*) and green sunfish (*Lepomis cyanellus*) were used in one experiment to determine the relative bioconcentration factors for these species. The fathead minnow was selected because it is readily available, easily cultured in the laboratory, and the laboratory-derived BCF for fathead minnows is comparable to those estimated for warmwater fishes in the environment. Test fish were obtained from the Environmental Research Laboratory—Duluth (ERL—D) culture. Adult fathead minnows (~6 mo old) were used rather than juvenile fish for the bioconcentration test because possible effects on growth are minimized, and the larger fish facilitate the residue analysis, especially when analyzing chemicals that do not accumulate to high concentrations in the fish.

The handling, holding, and acclimation procedures were those given by the U.S. Environmental Protection Agency Committee on Methods for Toxicity Tests with Aquatic Organisms (1975). In the tests involving temperature variations, the fish were acclimated to lower temperatures by decreasing the temperature ~2 deg C/d and holding fish at the test temperatures for a minimum of 1 wk before initiating the test. The fish were fed daily with frozen brine shrimp.

DeFoe et al. (1978) and Nebeker et al. (1974) showed that PCB residues in female fathead minnows during spawning were twice as great as those in male minnows, largely because of change in lipid content during spawning. During the early stages of this study, when spawning tiles were used in the exposures to reduce the excitability of the fish, occasional spawning was observed. The relative standard deviation of the residue concentrations after 32d in a PCB test was 46.6% of the mean. By removing the spawning tiles and reducing the light intensity and duration, a similar exposure resulted in a relative standard deviation of 11.4% of the mean.

Test Method

One day before testing, 35 fish were transferred to a control tank, and the addition of the test chemical to the test tank was begun by metering in an acetone solution of the chemical. After verification of the desired concentration of chemical in the test tank, 30 of the fish were transferred to a test tank, and the remaining fish remained in the control tanks for the duration of the test. The concentration of chemical in the water was measured each weekday. Samples of five fish were removed after 2, 4, 8, 16, 24, and 32 d of exposure, frozen, and analyzed for residues. The first five samples were analyzed as a composite, but the 32-d samples were generally analyzed individually to determine the mean and standard deviation of the composite residues.

Analytical Methods

The water samples were siphoned from the tank directly into a 500-mL volumetric flask to which 25 mL hexane had been added previously. When filled to the calibrated mark, the flask contained 475 mL water and 25 mL hexane. In the analysis of phenols 1 mL of concentrated H_2SO_4 was added to reduce the pH for more complete extraction.

A teflon-coated stirring bar was placed in the flask, and the mixture was rigorously stirred to create vortex mixing for 1.5 h. The phases were allowed to separate for 1 h, and a 1.4-mL aliquot of hexane was transferred to a Hewlett–Packard gas-chromatography injection vial. The analysis was based on the 25-mL vol of hexane initially placed in the sampling flask. Phenol samples were treated with 100 μL of BSA (Pierce Chemical Co.) to form the trimethylsilyl derivation for analysis.

When radiolabeled chemicals were used, 5 mL of the hexane extract was transferred to a scintillation vial containing 15 mL of Permafluor IV cocktail. The activity was measured with a Packard Tri-Carb scintillation counter and a 10-min counting time. A quench curve was calculated daily, and a counting efficiency >0.60 was observed throughout the tests.

Fish samples were homogenized as whole fish with anhydrous Na_2SO_4 in a blender. The powdered homogenate was transferred to a Soxhlet extraction thimble and exhaustively extracted for 4 h with 200 mL of a mixture of methylene chloride and hexane (1:1). For pesticides and related nonpolar chemicals, the extracts were cleaned up with chromatographic separations on Florisil. Polar residues were isolated from the lipids in the extract with gel-permeation chromatography (Kuehl and Leonard 1977). Radiolabeled residues were measured by counting an aliquot of the extract in Permaflour I cocktail.

Gas-chromatographic analyses were performed on a Hewlett–Packard 5700A gas chromatograph equipped with an autosampler, Hewlett–Packard Model 3352A data system, and a ^{63}Ni electron capture detector. The column was a 2 × 3-mm (OD) glass column packed with 800/100 mesh Gas Chrom Q coated with 4/6% SE-30/OV-210. The carrier gas was 5% methane in argon, and the temperature was adjusted between 140 and 220°C as appropriate for the chemical being analyzed.

The accuracy of the analytical methods was examined by determining the recovery of known amount of the chemical in water or tissue. The experimental procedures were adjusted so that at least 90% of the added chemical was recovered. The water and tissue concentrations were not corrected for recovery in the calculation of bioconcentration factors.

Results

Effect of Age of Test Fish

The effect of age of the fathead minnow on the BCF was determined by exposing fish from four age-groups (newly hatched larvae, juvenile minnows 30 and 90 d old, and adult minnows) to ~5 μg/L hexachlorobenzene for 32–120 d. The age of the fish had little effect on the measured BCF at 24°C (Fig. 1). The measured log BCF was 4.22 for the adult fish, 4.26 for the 30-d-old fish, 4.25 for the 90-d-old fish, and 4.66 in the fry hatched in the test chambers. The BCF for hexachlorobenzene in fry was slightly larger than the other ages of fish, which probably resulted from the difference in diet used for the fish before testing. Although the data indicated that the bioconcentration test with 30-d-old fish would be comparable to that begun with 90-d-old fish or adults, the small size of 30-d-old fish is a disadvantage with respect to

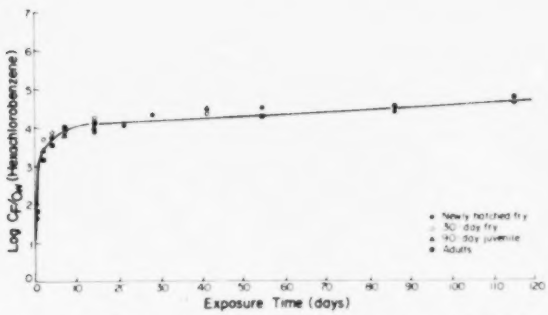

FIG. 1. Uptake of hexachlorobenzene in four age-classes of fathead minnows (*Pimephales promelas*).

the analysis, particularly when testing chemicals with small BCF.

EFFECT OF SOURCE OF TEST FISH

To determine the precision of the BCF calculated from the laboratory exposure, we performed replicate tests and repeated tests with fathead minnows from several sources. The PCB mixture Aroclor® 1016 was tested with three different groups of adult minnows from the ERL-D culture unit over a 3-yr period. Also, two groups of fathead minnows from a private farm pond were used in duplicate tests to determine the bioconcentration factor of Aroclor® 1016. The source of fathead minnows had little effect on the measured BCF (Table 1). The geometric mean of the log BCF was 4.61 for the three tests with laboratory fish and 4.69 for fish from a farm pond. The overall mean log BCF was 4.65 ± 0.08, which corresponds to a BCF of $44\,300 \pm 12\,000$.

EFFECT OF TEMPERATURE AND DIFFERENT TEST SPECIES

The use of different test species and different test temperatures makes the comparison of results from various laboratories difficult. To determine the effect of temperature on BCF values we determined the BCF

TABLE 1. Bioconcentration factor (BCF) of the PCB mixture Aroclor® 1016 as determined with adult fathead minnows from two sources.

Source of minnows	Test date	Test duration (d)	BCF	Log BCF
ERL-D culture		32	50 000	4.70
ERL-D culture		32	30 200	4.47
ERL-D culture		32	42 700	4.63
Private farm pond		30	37 200	4.57
Private farm pond		30	61 500	4.79
Mean			44 300	4.65
SD			12 000	0.08

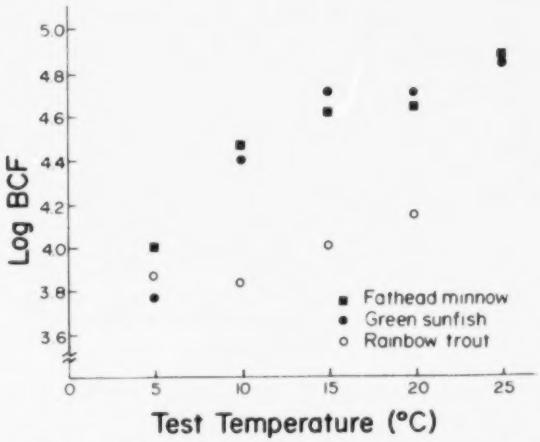

FIG. 2. Variation in BCF of Aroclor® 1254 with exposure temperatures for fathead minnows, green sunfish (*Lepomis cyanellus*), and rainbow trout (*Salmo gairdneri*).

of the same chemical with three commonly used test species over a range of test temperatures. Adult fathead minnows, rainbow trout fingerlings, and juvenile green sunfish were exposed to the PCB mixture Aroclor® 1254 at 5, 10, 15, 20, and 25°C. The 32-d log BCF of Aroclor® 1254 in fathead minnows increased from 4.04 at 5°C to 4.88 at 25°C (Fig. 2). The log BCF with green sunfish increased from 3.77 at 5°C to 4.84 at 25°C. The BCF for Aroclor® 1254 is approximately the same when measured with fathead minnows and green sunfish on a whole-fish basis (Fig. 2). The log BCF for Aroclor® 1254 in trout increased from 3.87 at 5°C to 4.15 at 20°C. Rainbow trout were not tested at 25°C. The BCF measurements for the three species differ little at 5°C. However, fathead minnows and green sunfish have a large temperature dependence on uptake up to ~15°C, whereas rainbow trout have only a slight temperature dependence. Fatheads and sunfish accumulate 3 times more PCB residues than rainbow trout at 20°C.

This relationship was further documented by exposing fathead minnows, green sunfish, and rainbow trout to hexachlorobenzene and 1,2,4-trichlorobenzene at 15°C (Table 2). The trout BCF was approximately one third the BCF for the minnow or the sunfish. Trichlorobenzene was bioconcentrated ~2.5 times more in minnows and sunfish than in the trout fingerlings.

SIMULTANEOUS MULTIPLE EXPOSURES TO CHEMICAL

The experiments with PCB mixtures resulted in PCB residues that were essentially identical in composition to the Aroclor® mixtures used in the exposure. If the bioconcentration process is largely controlled by the partitioning of the chemicals between water and the lipids in the gill tissue, blood, and the body, it is

TABLE 2. Bioconcentration factors of hexachlorobenzene and trichlorobenzene in three test species at 15 C.

Species	BCF[a]	Log BCF
	Hexachlorobenzene	
Fathead minnow	16 200	4.21
Green sunfish	21 900	4.34
Rainbow trout	5 500	3.74
	1,2,4-Trichlorobenzene	
Fathead minnow	2 100	3.32
Green sunfish	2 300	3.37
Rainbow trout	890	2.95

[a]Average of two individual exposures.

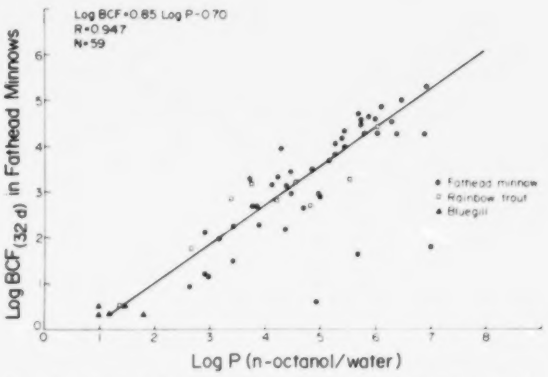

FIG. 3. Correlation of log BCF with log P for organic chemicals.

reasonable to expect that the uptake of chemical in mixtures is independent of the other chemicals, providing the organism metabolism is not significantly altered by one of the chemicals. To test this hypothesis, we exposed fathead minnows to p,p'DDE and heptachlor expoxide individually and as a mixture. The 32-d BCF of p,p'DDE was 60 000 exposed independently and 64 500 in the presence of heptachlor expoxide. The 32-d BCF of heptachlor expoxide was 14 400 exposed independently and 13 200 when exposed in the presence of p,p'DDE, well within the expected variability of the individual tests.

Thus it may be possible to test more than one chemical in each exposure if the chemicals can be analyzed accurately in the presence of each other. The time and expense of bioconcentration testing would be greatly reduced because fewer fish and fewer measurements would be required. Moreover, if p,p'DDE were adopted as an "internal standard" and tested simultaneously with all chemicals, the calculation of a BCF relative to the BCF of p,p'DDE would reduce the difficulties in comparing the results of laboratories where different experimental conditions and species are used. The development of a data base of relative BCF values by using a benchmark chemical such as p,p'DDE would be a major step in extending the use of bioconcentration tests with fish to determine the bioaccumulation potential of organic chemicals in all levels of the aquatic food chain.

BIOCONCENTRATION TESTS

Thirty chemicals were tested for bioconcentration with the fathead minnow in 32-d exposures (Table 3). The measured logarithm of the bioconcentration factors ranged from 0.44 for tris (2,3-dibromopropyl) phosphate to 5.28 for the Aroclor® 1260 PCB mixture. With the exception of hexachlorocyclopentadiene and chlorinated paraffins, the nonhalogenated chemicals had log BCF values of <2.0–2.5. Chemicals containing more than five halogens were generally bioconcentrated by the fish more than 5000 times the concentration of the chemical in the water. The addition of a polar functional group to the chemical substantially reduced the BCF. For example, the log BCF for hexachlorobenenze was 4.27, whereas the log BCF for pentachlorophenol was only 2.89.

Discussion

The logarithm of the n-octanol/water partition coefficient (abbreviated log P) is a commonly used indicator of the lipophilic nature of chemicals. For log P to be useful as a predictor of BCF in screening tests, the relationship between BCF and log P must be established empirically from the results of testing a wide variety of chemicals. The remainder of discussion in this report will be concerned with correlating log BCF and log P for organic chemicals.

A summary of bioconcentration test results and log P values from a variety of experimental conditions from other studies as well as the data from this study is presented in Table 4. The log P values were taken from the references indicated or were estimated by the reverse-phase high-pressure liquid chromatography method of Veith and Morris (1978). These data will serve as the basis for the discussion of the relationship between log P and the bioconcentration factor. The rainbow trout BCF data were from a single laboratory, and, because our Aroclor® 1254 experiment with three species indicated that log BCF values for trout were ~0.5 U less than those from fathead minnows or green sunfish, a value of 0.5 was added to the trout exposures before including these data in the correlations. Currently, we have no data to confirm that this factor is appropriate for chemicals that have smaller bioconcentration factors.

The log BCF and n-octanol/water partition coefficient as log P are linearly correlated (Fig. 3). The correlation for the 55 tests can be expressed by the equation,

$$\log \text{BCF} = 0.85 \log P - 0.70,$$

which has a correlation coefficient (r^2) of 0.897. This

TABLE 3. Log BCF and bioconcentration potential (DDE = 100) for 30 organic chemicals as determined with the fathead minnow in 32-d exposures.

Chemical	Mean exposure C_W (μg/L)	Log BCF	BCF	Bioconcentration potential[a]
tris-(2,3-dibromopropyl-phosphate	47.7	0.44	2.7	<0.1
5-bromoindole	4.3	1.15	14	<0.1
hexachlorocyclopentadiene	20.9	1.47	29	<0.1
diphenylamine	43.7	1.48	30	<0.1
chlorinated paraffin	49.2	1.69	49	<0.1
toluene diamine	1.0	1.96	91	0.2
N-phenyl-2-naphylamine	52.1	2.17	147	0.3
tricresyl phosphate	31.6	2.22	165	0.3
lindane	3.4	2.26	180	0.4
pentachlorophenol	11.1	2.89	770	1.5
2,4,6-tribromoanisole	4.8	2.94	865	1.7
1,2,4-trichlorobenzene	1.6	3.32	2 800	5.5
hexachloronorbornadiene	b	3.81	6 400	13
methoxychlor	3.5	3.92	8 300	16
heptachlor	3.1	3.98	9 500	19
heptachloronorbornene	—[b]	4.05	11 100	22
heptachlorepoxide	1.3	4.16	14 400	28
mirex	1.2	4.26[c]	18 100	35
hexabromocyclododecane	6.2	4.26	18 100	35
hexabromobiphenyl	5.3	4.26	18 100	35
hexachlorobenzene	2.6	4.27	18 500	36
*p,p'*DDT	6.5	4.47[c]	29 400	58
octachlorostyrene	7.1	4.52	33 000	65
*op'*DDT	5.1	4.57[c]	37 000	72
chlordane	5.9	4.58	37 800	74
Aroclor® 1016	8.7	4.63[d]	42 500	83
*p,p'*DDE	7.3	4.71[e]	51 000	100
Aroclor® 1248	4.0	4.85	70 500	138
Aroclor® 1254	4.3	5.00[e]	100 000	196
Aroclor® 1260	1.0	5.28	194 000	300

[a]Bioconcentration potential calculated relative to *p,p'*DDE = 100.
[b]Calculated from bioassay with these chemicals.
[c]Geometric mean of two tests.
[d]Geometric mean of five tests.
[e]Geometric mean of three tests.

TABLE 4. Reported values of log BCF and log *P* of chemicals determined with a variety of testing methods.

Chemical	Log BCF	Exposure period (d)	Species	Log *P*	Reference
lindane	2.67	304	Fathead minnow	3.85	Macek et al. 1976a
atrazine	<0.90	276	Fathead minnow	2.63	Macek et al. 1976b
heptachlor	4.30	276	Fathead minnow	5.44	Macek et al. 1976c
2-ethylhexiphthalate	2.93	56	Fathead minnow	4.20	Mayer 1976
DASC-3	<0.32	30	Bluegill	1.0	Gonz et al. 1975
DASC-4	<0.32	30	Bluegill	1.0	Gonz et al. 1975
NTS-1	0.32–1.00	35	Bluegill	1.0	Gonz et al. 1975
BSB	<0.32	50	Bluegill	1.0	Gonz et al. 1975
FWA-2-A	<0.32	105	Bluegill	1.80	Sturm et al. 1975
FWA-3-A	<0.32	105	Bluegill	1.48	Strum et al. 1975
FWA-4-A	<0.32	105	Bluegill	1.20	Strum et al. 1975
nitrobenzene	1.18	28	Fathead minnow	2.93	Call and Brook 1977[b]
p-nitrophenol	2.10	28	Fathead minnow	2.91	Call and Brook 1977
naphthalene	2.63	28	Fathead minnow	4.70	Call and Brook 1977
chlorobenzene	2.65	28	Fathead minnow	3.79	Call and Brook 1977

TABLE 4 (*Continued*)

Chemical	Log BCF	Exposure period (d)	Species	Log *P*	Reference
2,4,5-trichlorophenol	3.28	28	Fathead minnow	3.72	Call and Brook 1977
endrin	3.66	300	Fathead minnow	4.56	Jarvinan and Tyo 1979
1,1,2,2-tetrachloroethylene	1.59[a]	4	Rainbow trout	2.88	Neely et al. 1974
hexachlorobenzene	3.89[a]	4	Rainbow trout	5.23	Neely et al. 1974
p-biphenyl phenyl ether	2.74[a]	4	Rainbow trout	5.55	Neely et al. 1974
diphenyl ether	2.29[a]	4	Rainbow trout	4.21	Neely et al. 1974
carbon tetrachloride	1.24[a]	4	Rainbow trout	2.64	Neely et al. 1974
p-dichlorobenzene	2.33[a]	4	Rainbow trout	3.38	Neely et al. 1974
biphenyl	2.64[a]	4	Rainbow trout	3.76	Neely et al. 1974
chloropyrifos	2.67	35	Mosquitofish	4.82	Neely et al. 1974
endrin	3.17	35	Mosquitofish	4.56	Neely et al. 1974
2,5,6-trichloropyridinol	0.49	35	Mosquitofish	1.35	Neely et al. 1974
fluorene	3.11	28	Fathead minnow	4.38	Carlson et al. 1978[c]
dibenzofuron	3.13	28	Fathead minnow	4.12	Carlson et al. 1978
2-chlorophenanthene	3.63	28	Fathead minnow	5.16	Carlson et al. 1978
phenanthrene	3.42	4	Fathead minnow	4.46	Carlson et al. 1978
2-methylphenanthrene	3.48	4	Fathead minnow	4.86	Carlson et al. 1978
Log BCF and log *P* calculated from this study (32-d exposures with fathead minnows)					
heptachlor	3.98			5.44	
heptachlor expoxide	4.16			5.40	
*p,p'*DDE	4.71			5.69	
pentachlorophenol	2.89			5.01	
hexabromobiphenyl	4.26			6.39	
methoxychlor	3.92			4.30	
mirex	4.26			6.89	
hexabromocyclododecane	4.26			5.81	
hexachlorocyclopentadiene	1.47			5.51	
heptachloronorbornene	4.05			5.28	
hexachloronorbornadiene	3.81			5.28	
Aroclor® 1016	4.63			5.88	
Aroclor® 1248	4.85			6.11	
Aroclor® 1254	5.00			6.47	
Aroclor® 1260	5.29			6.91	
chlordane	4.58			6.00	
octachlorostyrene	4.52			6.29	
*p,p'*DDT	4.47			5.75	
*op'*DDT	4.57			5.75	
hexachlorobenzene	4.27			5.23	
1,2,4-trichlorobenzene	3.32			4.23	
lindane	2.26			3.89	
5-bromoindole	1.15			2.97	
2,4,6-tribromoanisol	2.94			4.48	
N-phenyl-2-naphylamine	2.17			4.38	
tris (2,3-dibromopropyl) phosphate	0.44			4.98	
tricresyl-phosphate	2.22			3.42	
chlorinated ecosane	1.69			7.05	
diphenyl amune	1.48			3.42	
toluene diamine	1.96			3.16	

[a]Calculation based on wet weight, muscle concentration.

[b]D. Call and L. Brook, 1977, University of Wisconsin-Superior, Center for Lake Superior Studies, Superior Wisconsin, unpublished data.

[c]R. M. Carlson, A. R. Oyler, E. H. Gerhart, R. Caple, K. J. Welch, H. L. Kopperman, P. Bodenner, and D. Swenson. 1978. Environmental impact of polynuclear aromatic hydrocarbon carbons liberated from Northern Great Plains coal. University of Minnesota—Duluth, Department of Chemistry, Final Report EPA Grant R803952-03-1, 169 p.

correlation suggests that the log BCF can be estimated to within an order of magnitude for chemicals having a range of 10 000 000 in the partition coefficients.

Hexachlorocyclopentadiene, tris (2,3-dibromopropyl) phosphate, and chlorinated ecosane were omitted from the correlation because the bioconcentration tests indicated that these chemicals bioconcentrate very little despite their comparatively large log P values. While there may be other chemicals with a large log P value that do not bioconcentrate significantly, these data are anomalous to the relationship between the log P and the log BCF shown in the correlation in Fig. 3.

Log P can be used to estimate the log BCF of an untested chemical at a fraction of the cost of bioconcentration testing. The anomalies observed in this study constitute ~5% of the chemicals tested. Moreover, no examples were observed in which the log BCF measured in the testing was much larger than that indicated from the log P estimates determined by using this correlation. The correlation may predict the maximum log BCF, but the only certain estimate will be to conduct the bioconcentration test.

The laboratory-derived BCF is only a conservative estimate of the residues likely to occur in the environment because residues may arise from both bioconcentration (partitioning) of the chemicals through the gills and biomagnification (ingestion) of the chemicals from the food supply. Although some data indicate that the laboratory BCF values for fathead minnows are similar to field BCF values for small fish in rivers (Veith and Lee 1971; Nadeau and Davis 1976; Snarski and Puglisi 1976; and DeFoe et al. 1978), the fish-residue concentration and corresponding water concentration in large reservoirs and lakes such as the Great Lakes are as much as an order of magnitude greater than the BCF determined from the laboratory (Veith et al. 1977). This difference may indicate that the uptake rate through the gills at low water concentrations is small compared to the uptake rate from ingestion of the chemicals in the diet. Weininger (1978) has concluded that bioconcentration of PCBs in Lake Michigan lake trout constitutes only ~1% of the total residue of PCBs, the remainder arising from the sediment-based food chain.

Despite the conservative nature of the bioconcentration factor, these measurements can be of considerable value to environmental studies if the BCF measured in the laboratory is considered as a bioaccumulation potential rather than an absolute bioaccumulation factor. The required assumption is that if the behaviour of several chemicals can be adequately modeled in large aquatic ecosystems to relate chemical loading factors and fish residues, then the behavior of other chemicals can be estimated from the relative bioconcentration factors.

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